# ENTHALPY OF VX HYDROLYSIS IN AQUEOUS SODIUM HYDROXIDE SOLUTION AT 90 °C

Philip W. Bartram, Elaina H. Harrison, Robert S. Lindsay, Suzanne A. Procell, and Robin L. Matthews, Applied Test Team, Research and Technology Directorate, Edgewood Chemical Biological Center, Aberdeen Proving Ground, MD 21010

## ABSTRACT

The enthalpy ($\Delta H$) or heat of reaction ($\mathbf{q_r}$) for the hydrolysis of munitions grade VX (O-ethyl S-2-diisopropylaminoethyl methylphosphonothiolate) in aqueous sodium hydroxide (20.4 wt % or 5.01 M) at 90 °C was determined in a 2-Liter Mettler RC1 Reaction Calorimeter. Typically, VX (680.2 g ± 4.1 or 2.548 moles) with dicyclohexylcarbodiimide (DCCDI) as a stabilizer was added to the sodium hydroxide solution (1377.1 g ± 5.4) in the reactor at 11.35 g/min. The average normalized enthalpy for nine reactions was -139.6 kJ ($S_{N-1}$ 4.2)/mole VX. The overall heat transfer coefficient ($\mathbf{U_{Final}}$) of the final reaction mass was 178.3 (W/(m$^2$ °K)) $S_{N-1}$ 7.7, and the specific heat capacity ($\mathbf{C_{pr\ (Final)}}$) was 3.6 (kJ/(kg °K)) $S_{N-1}$ 0.2. Further, $\Delta H$ for the reaction of VX (599.8 g ± 0.40 or 2.25 moles) with diisopropylcarbodiimide (DICDI) in aqueous NaOH (5.01 M, 1211 g) was -141.2 kJ ($S_{N-1}$ 4.7)/mole VX. The thermodynamic quantities ($\Delta H$ and $\mathbf{C_{pr}}$) were not significantly different (Student's t-Test, $\alpha = 0.95$) than previous reported data.

## INTRODUCTION

The chemical warfare agent O-ethyl S-2-diisopropylaminoethyl methylphosphonothiolate (VX) is a persistent, colorless, and extremely toxic liquid.[1] VX (M.W. = 267.36, d. = 1.008 g/mL at 25 °C) is a pentavalent organophorphorus ester that irreversibly inhibits the enzyme acetylcholinesterase (AChE) through phosphonylation of serine hydroxyl.[2, 3, 4, 5] The routes of exposure can be through inhalation, ingestion, and percutaneous contact. The function of AChE is to catalyze the hydrolysis of acetylcholine, the neurotransmitter, which generates a postsynaptic action potential that initiates organ activity.[4, 5, 6] Accumulation of acetylcholine causes excessive organ activity and, eventually, death due to respiratory paralysis.[4, 5, 6]

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE<br>**01 OCT 2005** | 2. REPORT TYPE<br>**N/A** | 3. DATES COVERED<br>**-** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**Enthalpy Of Vx Hydrolysis In Aqueous Sodium Hydroxide Solution At 90 °C** | 5a. CONTRACT NUMBER |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**Applied Test Team, Research and Technology Directorate, Edgewood Chemical Biological Center, Aberdeen Proving Ground, MD 21010** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR’S ACRONYM(S) |
| | 11. SPONSOR/MONITOR’S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release, distribution unlimited**

13. SUPPLEMENTARY NOTES
**See also ADM001851, Proceedings of the 2003 Joint Service Scientific Conference on Chemical & Biological Defense Research, 17-20 November 2003. , The original document contains color images.**

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **UU** | **7** | |

The reaction rate, products, and ratio of products of VX hydrolysis under basic conditions are pH and temperature dependent. The hydrolysis of VX in neutral to weakly basic solution at 23 °C results in two major P(V) products, O-ethyl methylphosphonic acid (**a**) and S-(2-diisopropylaminoethyl) methylphosphonothioic acid (**b**), and a minor P(V) product – O-ethyl methylphosphonothioic acid (**c**).[7, 8] However, the ratio of products as determined by $^{31}$P NMR for VX (1.0 wt %) heated in water for 2 h was 40/20/40 for **a**, **b**, and **c**, respectively.[8] The kinetic rate of hydrolysis at 23 °C versus pH fits the equation $k_{obs} = k_i + k_{OH}[OH^-]$ with $k_{OH} = 5.19 \times 10^{-3}\ M^{-1}\ S^{-1}$ to pH 13.[8]

The hydrolysis of VX in strongly basic solution provides only P(V) products **a** and **b**.[8] As the concentration of hydroxide is increased from 0.5 M to 4.0 M, the ratio of **a** to **b** decreases.[8] O-ethyl methylphosphonothioic acid is quite stable at room temperature, but can be hydrolyzed at a moderate rate ($t_{1/2}$ = 35.0 min) in 2.0 M hydroxide at 75 °C.[8]

The Program Manager for Alternative Technologies and Approaches (PMATA) has selected a hot caustic hydrolysis process for the neutralization of militarized VX. In the process, VX will be pumped into a stirred reactor containing 20.4 wt % NaOH solution at 90 °C. Several studies to support the process have been completed.[9, 10] Under the reaction conditions (*supra vide*), VX hydrolyzes initially to the salts of **a**, **c**, 2-diisopropylaminoethyl mercaptan (**d**), and ethanol.[9, 11] Compound **c** reacts further to methylphosphonate and **d**.[9] Additional characterization of the reactions included $\mathbf{q_r}$, $\mathbf{C_{pr}}$, and the heat transfer parameters.

In this paper, further characterization of the thermodynamics for the PMATA reaction is provided. The $\mathbf{\Delta H}$, $\mathbf{U_{Final}}$, and $\mathbf{C_{pr\ (Final)}}$ were determined for two new ton container lots of munitions VX and the data compared statistically to previous values.

## EXPERIMENTAL METHODS

### Materials

VX-S-6228-CTF-N-2 (purity = 82.0 area %, assayed 4 June 2003 by GC/MS) containing 0.8 area % dicyclohexylcarbodiimide (DCCDI) and VX9009-36903-05 (purity = 93.7 area %, assayed 19 June 2003) containing 4.9 area % diisopropylcarbodiimide (DICDI) were obtained from the Chemical Transfer Facility. Sodium hydroxide (lot # 966778) was purchased from Fisher Scientific Company (Newark, DE). Water was taken from the laboratory tap; the water was not assayed.

### Equipment

The enthalpy was measured in a Mettler-Toledo RC1 Reaction Calorimeter. The calorimeter system consisted of a glass-jacketed 2-liter reactor with glass baffle, an overhead agitator motor with impeller, a heat transfer reservoir, dosing controller, metering pump, and a constant temperature circulation bath. The process was controlled by Mettler-Toledo GmbH, Win RC V7.11 for RC1, Revision 800, software (Copyright© 2001). The WinRC1 software was run on a Dell OptiPlex GX200 computer with a Windows NT Workstation, Version 4, operating system. The Applied Test Team wrote a process template specifically for this study.

Reaction Calorimeter Tests

VX (O-ethyl S-2-diisopropylaminoethyl methylphosphonothiolate) was added to aqueous sodium hydroxide (20.4 wt % or 5.01 M) at 90 °C in a 2-Liter reactor. Typically, VX was feed into the sodium hydroxide solution at 11.35 g/min. Stirring with a four-bladed 2” Rushton turbine radial flow impeller was maintained at 950 rpm, and a nitrogen purge was used to eliminate $CO_2$ from the reactor during the reactions. The virtual volume and calorimetric measurements were determined before and after the addition of VX.[12] Reaction conditions were maintained for two hours after the addition of VX, then a sample was assayed by GC/MS to determine the extent of reaction. The **ΔH, $\mathbf{U_{Final}}$,** and $\mathbf{C_{pr\ (Final)}}$ were calculated by the WinRC1 software.

## RESULTS

An acetic anhydride in water reaction was used to calibrate the Mettler calorimeter. The ΔH for the reactions (n = 3) was $\bar{x}$ = 55 kJ $S_{N-1}$ 1.8/mole of acetic anhydride, which was similar to previous measurements.[9] VX-S-6228-CTF-N-2 ($\bar{x}$ = 680.2 g $S_{N-1}$ 4.1) was added to aqueous sodium hydroxide ($\bar{x}$ = 1377.1 g $S_{N-1}$ 5.4) at 90 °C. The feed rate was 11.35 g/min. The calculated ΔH for the reactions (n = 9) was -139.6 kJ ($S_{N-1}$ 4.2) /mole VX. In another set of reactions, VX9009-36903-05 ($\bar{x}$ = 599.8 g $S_{N-1}$ 0.4) was added to aqueous sodium hydroxide ($\bar{x}$ = 1207.7 g $S_{N-1}$ 0.6) at the same rate. The average enthalpy for the reactions (n = 3) was -141.2 kJ ($S_{N-1}$ 4.7)/mole VX. The values were calculated based on the assumption that the purity of the agents was 100%. There was no significant difference in ΔH for the two sets of reactions ($P_{value}$ = 0.5894 at $\alpha$ = 0.05).[13] A previous study reported that the enthalpy for the reaction (n = 3) was -143.3 kJ ($S_{N-1}$ 2.8)/mole VX.[9, 14, 15] The previous reported ΔH was not significantly different than the values obtained in the VX-S-6228-CTF-N-2 ($P_{value}$ = 0.1913 $\alpha$ = 0.05) and VX9009-36903-05 ($P_{value}$ = 0.5425 $\alpha$ = 0.05) reactions. The reaction data are provided in Table 1. Equations for the thermodynamic quantities are provided in Table 2.

The heat transfer coefficient (**U**) was determined at 85 °C and 90 °C before and after dosing with VX. In this study only the 90 °C value obtained after the addition of VX is reported. The average $\mathbf{U_{Final}}$ for the VX-S-6228-CTF-N-2 reactions (n = 8) was

TABLE 1. Data for the Hydrolysis of VX in 20.4 wt % Aqueous Sodium Hydroxide at 90 °C

| REACTION NUMBER | AGENT LOT/ STABILIZER | AMOUNT OF VX (g) | AMOUNT OF NAOH SOLUTION (g) | ΔH (kJ/mole VX) | $U_{FINAL}$ ($W/(m^2\ °K)$) (90 °C) | $C_{PR\ (FINAL)}$ (kJ/(kg °K)) (90 °C) | [VX] 2h |
|---|---|---|---|---|---|---|---|
| M-1-01-VN-3156 | VX-S-6228-CTF-N-2 (DCCDI) | 669.2 | 1377 | -148.38 | 179.5 | 3.63 | [b]<MDL |
| M-2-01-VN-3160 | VX-S-6228-CTF-N-2 (DCCDI) | 681.6 | 1377 | -138.50 | 179.3 | 3.59 | <MDL |
| M-3-01-VN-3161 | VX-S-6228-CTF-N-2 (DCCDI) | 681.2 | 1375 | -138.95 | 168.7 | 3.41 | <MDL |
| M-4-01-VN-3162 | VX-S-6228-CTF-N-2 (DCCDI) | 681.2 | 1377 | -134.93 | NA | 3.25 | <MDL |
| M-5-01-VN-3163 | VX-S-6228-CTF-N-2 (DCCDI) | 681.3 | 1374 | -136.57 | 178.6 | 3.57 | <MDL |
| M-6-01-VN-3167 | VX-S-6228-CTF-N-2 (DCCDI) | 681.6 | 1375 | -137.10 | 165.2 | 3.38 | 20 ppm |
| M-7-01-VN-3168 | VX-S-6228-CTF-N-2 (DCCDI) | 682.0 | 1391 | -137.41 | 182.4 | 3.70 | <MDL |
| M-8-01-VN-3173 | VX-S-6228-CTF-N-2 (DCCDI) | 681.8 | 1375 | -140.39 | 185.3 | 3.70 | <MDL (3 h) |
| M-9-01-VN-3175 | VX-S-6228-CTF-N-2 (DCCDI) | 681.5 | 1373 | -143.76 | 187.4 | 3.83 | <MDL |
| M-11-01-VN-3181 | VX9009-36903-05 (DICDI) | 599.3 | 1208 | -140.31 | 192.8 | 3.54 | <MDL |
| M-12-01-VN-3182 | VX9009-36903-05 (DICDI) | 600.0 | 1208 | -146.23 | 196.8 | 3.44 | <MDL |
| M-13-01-VN-3183 | VX9009-36903-05 (DICDI) | 600.0 | 1207 | -136.95 | 185.7 | 3.57 | <MDL |
| **MT-1-01-VN-3156 through MT-9-01-VN-3175** | | [a] $\bar{x} = 680.2$ $S_{n-1} = 4.1$ | $\bar{x} = 1377.1$ $S_{n-1} = 5.4$ | $\bar{x} = -139.6$ $S_{n-1} = 4.2$ | $\bar{x} = 178.3$ $S_{n-1} = 7.7$ | $\bar{x} = 3.6$ $S_{n-1} = 0.2$ | NA |
| **MT-11-01-VN-3181 through MT-13-01-VN-3183** | | $\bar{x} = 599.8$ $S_{n-1} = 0.4$ | $\bar{x} = 1207.7$ $S_{n-1} = 0.6$ | $\bar{x} = -141.2$ $S_{n-1} = 4.7$ | $\bar{x} = 191.8$ $S_{n-1} = 5.6$ | $\bar{x} = 3.5$ $S_{n-1} = 0.1$ | NA |

**[a]Final values have been rounded-off to nearest tenths. [b]MDL is minimum detection limit (10 µg/mL) of GC/MSD. PPM is parts per million. NA is either not applicable or not available.**

178.3 (W/($m^2$ °K) $S_{n-1}$ 7.7. The value was significantly smaller ($P_{value}$ = 0.023 $\alpha$ = 0.05) than $\mathbf{U_{Final}}$ obtained from the VX9009-36903-05 reactions (191.8 (W/($m^2$ °K) $S_{n-1}$ 5.6). The $\mathbf{U_{Final}}$ for the VX-S-6228-CTF-N-2 reactions was also significantly lower ($P_{value}$ = 0.0012 $\alpha$ = 0.05) than the previous reported value 203.5 W/($m^2$ °K) $S_{n-1}$ 8.8.[9] There was no statistical difference between the previous reported $\mathbf{U_{Final}}$ and the value obtained from the VX9009-36903-05 reactions.

TABLE 2. Formulas for the Calculations of Heat Terms

| | | |
|---|---|---|
| $\Delta H = \int (\mathbf{Qr - Qb}) \bullet \mathbf{dt}$ | | |
| **ΔH:** | Reaction enthalpy | kJ |
| **Qr:** | Heat generation rate, ∑ of selected heat flow terms | kJ |
| **Qb:** | Baseline for Qr | kJ |
| **U = Qf / (Tr –Ta)(A)** | | |
| **U:** | Overall heat transfer coefficient of the reactor wall | W/($m^2$ °K) |
| **Qf:** | Heat flow through the reactor wall | W |
| **A:** | Heat exchange area (wetted area) | $m^2$ |
| **Tr:** | Temperature of the reactor contents | °C |
| **Ta:** | Corrected temperature of the reactor contents | °C |
| $\mathbf{C_{pr} = Qa / mr (dTr/dt)}$ | | |
| $\mathbf{C_{pr}}$ | Specific heat capacity of the reaction mass | kJ/(kg °K) |
| **mr:** | Reaction mass (sum of all additions and dosings) | kg |
| **dTr/dt:** | Current change in the temperature of the reactor contents | K/s |

The $\mathbf{C_{pr}}$ (**Final**) for the reactions with VX-S-6228-CTF-N-2 was 3.6 kJ/(kg °K) $S_{n-1}$ 0.2. The quantity was not significantly different ($P_{value}$ = 0.4281) than the average $\mathbf{C_{pr}}$ (**Final**) for the VX9009-36903-05 reactions (3.5 kJ/(kg °K) $S_{n-1}$ 0.1). The previously reported value 3.6 kJ/(kg °K) $S_{n-1}$ 0.15[9] was not significantly different than the $\mathbf{C_{pr}}$ (**Final**) for the VX-S-6228-CTF-N-2 and VX9009-36903-05 reactions ($P_{value}$ = 0.89, $F_{value}$ = 0.117 and $F_{critical}$ = 3.89, ANOVA using Microsoft Excel).

## CONCLUSIONS

The reaction of VX in aqueous sodium hydroxide (5.01 M) at 90 °C was more exothermic than the hydrolysis of acetic anhydride. The ΔH or $\mathbf{q_r}$ for the reaction with VX-S-6228-CTF-N-2 was statistically similar to the VX9009-36903-05 reaction, although the purity was dissimilar. Apparently, the $\mathbf{q_r}$ for the reactions of sodium hydroxide with the impurities was equivalent to the reaction with VX.

## ACKNOWLEDGEMENT

The U.S. Army Program Manager for Alternative Technologies and Approaches (PMATA) funded this study. The authors thank Mr. Joseph Cambria, Mr. Michael Wasserman, and Dr. Dennis Rohrbaugh, Research and Technology Directorate, Edgewood Chemical Biological Center, for characterizing the VX samples.

## REFERENCES

1. Typically physical properties of VX are as follows: $ICT_{50}$ (50% of exposed human population will be incapacitated) = 25 mg X min/m$^3$ and $LCT_{50}$ (50% of the exposed human population will die without treatment) = 50 mg X min/m$^3$ for percutaneous vapor exposure; $ICT_{50}$ = 5 mg/70 kg man and $LCT_{50}$ = 10 mg/70 kg man for percutaneous liquid exposure; Freezing point < -51°C, Vapor pressure 0.093 Pa @ 25 °C, and volatility = 10.5 mg/m$^3$ @ 25 °C. MIL-HDBK-783 (EA), Chemical and Biological (CB) Contamination Avoidance and Decontamination, 15 October 1990.
2. M.W. is molecular weight and d. is density.
3. VX is not a refractory compound like GD, which "ages" (monodealkylation) rapidly after reacting with acetylcholinesterase. Reactivation (dephosphonylation) of the VX inhibited enzyme is possible if the antidote is administered quickly.
4. Timothy C. Marrs, Robert L. Maynard, and Frederick R. Sidell, Chemical Warfare Agents, Toxicology and Treatment, John Wiley and Sons Ltd, Baffins Lane, Chichester, West Sussex, England, 1996.
5. Satu M. Somani (Editor), Chemical Warfare Agents, Academic Press, Inc., San Diego, California, 1992.
6. Vladimir Vojvodic, Toxicology of War Gases, Federal Ministry for National Defense and Health Administration, Military Publishing House, Institute for Military Medical Information and Documentation, Belgrade, Yugoslavia, 1981.
7. S-(2-diisopropylaminoethyl) methylphosphonothioic acid is extremely toxic. The compound is about 3.5 times less toxic than VX.
8. Yu-Chu Yang, "Chemical Detoxification of Nerve Agent VX," *Accounts of Chemical Research*, Volume 32, Number 2, Pages 109-115, 1999.
9. PMCD, Stand-Alone Neutralization Bench Scale Test Report - Part 1, 2-Liter Reaction Calorimeter Tests Nerve Agent VX/Sodium Hydroxide, 4 November 1996.
10. PMCD, Stand-Alone Neutralization Bench Scale Test Report – Part 2 114-Liter Reactor Tests VX Nerve Agents/ Sodium Hydroxide, Volumes 1 and 2, 14 August 1996.

11. These were the principle products. Other products included ethyl methylphosphonothioic acid, Bis-[2-(diisopropylamino)ethyl] disulfide, and Bis-[2-(diisopropylamino)ethyl] sulfide.

12. Mettler-Toledo provides several technical manuals that describe the RC1 reactor, software, temperature measurements, and the treatment of data.

13. The statistical results were obtained from a Student's t-Test calculator available at graphpad.com. The two-tailed P-values are for unpaired data.

14. The agent used in the study was VX-S-5166-CTF-N-15, purity = 87.1 ± 2 wt %, assayed by GC/FID with an internal standard.

15. The reactants were 20 wt % sodium hydroxide (1197.97 g ± 2.5) and VX (605.73 g ± 0.2).